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ABSTRACT

Thin hydrogenated amorphous silicon (a-Si:H) layers deposited by hot-wire chemical vapor deposition (HWCVD) are used as both emitters and back contacts in silicon heterojunction solar cells. Low interface recombination velocity and high open-circuit voltage are achieved by a low substrate temperature ($<150^{\circ}\text{C}$) intrinsic a-Si:H deposition which ensures immediate amorphous silicon deposition. This is followed by deposition of doped a-Si:H at a higher temperature ($>200^{\circ}\text{C}$) which appears to improve dopant activation. With an i/n a-Si:H emitter, we obtain a confirmed efficiency of 17.1% on textured p-type float-zone (FZ) silicon with a screen-printed aluminum back-surface-field (Al-BSF) contact. Employing a-Si:H as both the front emitter and the back contact, we achieve a confirmed efficiency of 17.5%, the highest reported efficiency for a p-type c-Si based heterojunction solar cell.

1. Introduction

The silicon heterojunction (SHJ) is one of the most attractive device structures for fabrication of high-efficiency silicon solar cells at low temperatures ($<250^{\circ}\text{C}$) with simple processing. The excellent surface passivation provided by H and extra band bending due to the larger band gap of a-Si:H compared to c-Si makes well-designed a-Si:H emitters superior to conventional emitters made by dopant diffusion. Furthermore, a thin layer of a-Si:H, doped the same as the base wafer provides a back collector with very effective back-surface field that reduces the recombination velocity. The current conduction through the a-Si:H collector is adequate and no localized current conduction windows are needed, in contrast to dielectric back-surface passivation layers. These outstanding properties open the path to many a-Si/c-Si heterojunction silicon solar cell designs, the most successful being the Sanyo HIT cell [1] employing plasma-enhanced chemical vapor deposition (PECVD) to deposit thin p/i (emitter) and n/i (collector) a-Si:H layers on n-type wafers.

Great care must be taken in using PECVD to make high-efficiency SHJ cells because of the potential for plasma damage to the c-Si wafer surfaces. At NREL, hot-wire chemical vapor deposition (HWCVD) is used to eliminate the possibility of such ion damage. We have successfully used this technique to obtain record efficiencies for p-type silicon-wafer based heterojunction solar cells.

2 Results and Discussions

2.1 Single-Heterojunction SHJ Solar Cells – the a-Si:H Emitter

We use a standard Al-BSF on the back to optimize the a-Si:H emitter on the front. In a typical a-Si:H/c-Si heterojunction solar cell, a thin (~ 4 nm) intrinsic hydrogenated a-Si:H layer is interposed between the base wafer and the heavily doped emitter. Though such thin i-layers are difficult to characterize, i-layers likely have a far lower density of defects and a slightly larger energy gap than doped a-Si:H layers: both factors are advantageous for reducing dark current through the junction and increasing V_{oc} . If inadvertent epitaxy occurs during the i-layer deposition, it is unlikely to be of high quality. Further, if crystallinity extends through the i-layer, the rough c-Si interface can be contacted in places by the doped a-Si:H which is likely a less effective passivant than the i-layer. Any dark-current path through inadequately passivated interface states in a heterojunction solar cell reduces the open-circuit voltage (V_{oc}). Using HWCVD, we vary both the i- and n-layer deposition temperatures (T_d) to find the optimum conditions. It turns out that high V_{oc} values with (100) silicon wafers are obtained at temperatures below 150°C , but at temperatures higher than 200°C , V_{oc} is much reduced. This is because epitaxy is usually favored at i-layer deposition temperature $T_d > 200^{\circ}\text{C}$ while lower temperature ($T_d < 150^{\circ}\text{C}$) ensures abrupt a-Si:H deposition [2].

With an i-layer deposited at a low temperature of 100°C , we find that raising the n-layer deposition temperature to about 200°C provides the highest V_{oc} (see Figure 1). This seems to provide effective activation of the phosphorous dopant and a better quality n-layer. These optimizations on the a-Si:H emitter lead to 17.1% efficient single-side SHJ solar cells as shown in Table 1. This is a record for p-type c-Si based heterojunction solar cell using an Al back-surface field contact.

Table 1. Confirmed measurements of 1-cm² ITO/a-Si:H/c-Si/Al-BSF single-side solar cells on p-type c-Si substrates

ID	$V_{oc}(\text{V})$	$J_{sc}(\text{mA}/\text{cm}^2)$	F.F.(%)	$\eta(\%)$	Substrate
16C	0.645	33.11	79.2	16.9	1.0 $\Omega\cdot\text{cm}$ planar FZ
65C	0.652	32.16	80.5	16.9	0.5 $\Omega\cdot\text{cm}$ planar FZ
62A	0.636	34.96	76.8	17.1	1.0 $\Omega\cdot\text{cm}$ textured FZ

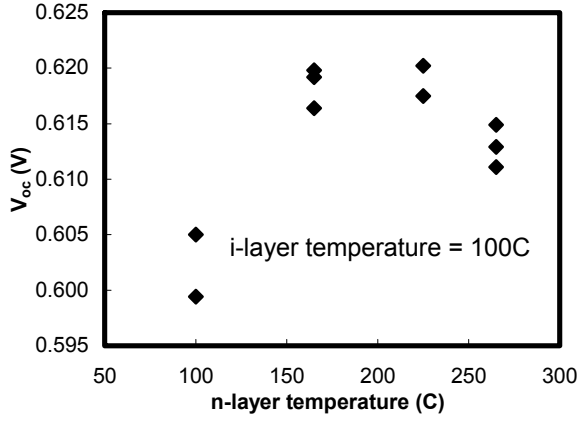


Fig. 1. Effect of n-layer deposition temperature on V_{oc} .

2.2 Double-Heterojunction SHJ Solar Cells – the a-Si:H Back Contact

Applying the best emitter a-Si:H deposition conditions to the backside passivation, we have fabricated simple double-heterojunction SHJ solar cells with a structure of ITO/a-Si:H emitter/c-Si/a-Si:H back contact.

Table 2. Effects of a-Si:H as emitter and back contact on V_{oc}

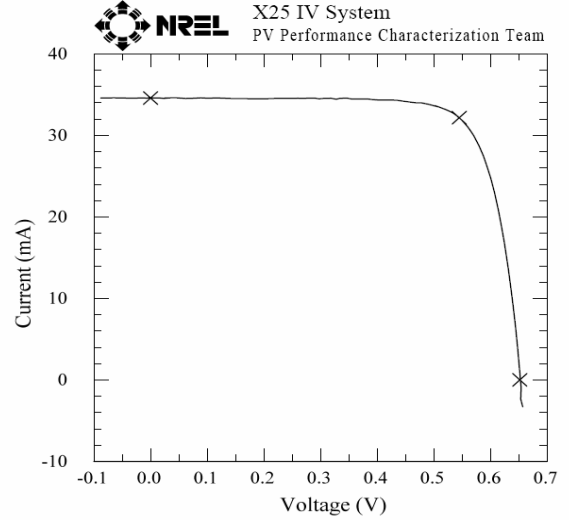
ID	V_{oc} (V)	Structure
5-5	0.63	diffused n+/planar p-FZ/Al-BSF
16C	0.65	a-Si(n/i)/planar p-FZ/Al-BSF
1540	0.65	a-Si(n/i)/textured p-FZ/Al-BSF
2933	0.66	a-Si(n/i)/textured p-FZ/a-Si(i/p)
2930	0.69	a-Si(p/i)/planar n-FZ/a-Si(i/n)

Table 2 illustrates the successive increases in V_{oc} by replacing a diffused junction with an a-Si:H emitter on the front and replacing an Al-BSF with an a-Si:H contact on the back. On textured $1.3 \Omega \cdot \text{cm}$ p-type FZ-Si, with an a-Si:H(i/p) back contact and a-Si(i/n) emitter, a V_{oc} of 0.66 V is obtained. Clearly, a-Si:H(i/p) contributes a stronger back-surface field than Al, without introducing problems in current collection. On planar $2.0 \Omega \cdot \text{cm}$ n-type FZ-Si, we obtain an even higher V_{oc} of 0.69 V. Of particular importance is that V_{oc} does not suffer from using a textured surface compared to a planar substrate. Using a textured bare FZ-Si wafer, we obtain a confirmed efficiency of 17.5% (see Figure 2), the highest reported for a p-type c-Si based heterojunction solar cell.

3 Conclusions

Effective a-Si:H/c-Si heterointerfaces with minimal recombination loss can be obtained using HWCVD. Abrupt a-Si:H(i) deposition and a flat hetero-interface to the c-Si substrate achieved at low-temperature ($<150^\circ\text{C}$) ensures that the a-Si:H contacts high quality c-Si with low interface defect density and high band bending while minimizing the a-Si:H/c-Si interface area. A higher temperature ($\sim 200^\circ\text{C}$) deposition of the subsequent doped layer enhances the

interface passivation and the built-in voltage, likely by activating dopants and reducing defect density in both the underlying i- and the doped-layer. When HWCVD a-Si:H is used as the back collector, a highly effective back-surface field is demonstrated by double-heterojunction SHJ devices with preliminary V_{oc} values of 691 mV and 660 mV on planar n-type FZ-Si and on textured p-type FZ-Si, respectively.



$V_{oc} = 0.6518 \text{ V}$	$I_{max} = 32.156 \text{ mA}$
$I_{sc} = 34.574 \text{ mA}$	$V_{max} = 0.5449 \text{ V}$
$J_{sc} = 34.574 \text{ mA/cm}^2$	$P_{max} = 17.521 \text{ mW}$
Fill Factor = 77.75 %	Efficiency = 17.52 %

Fig. 2. IV-curve of the 1-cm^2 double-heterojunction cell.

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